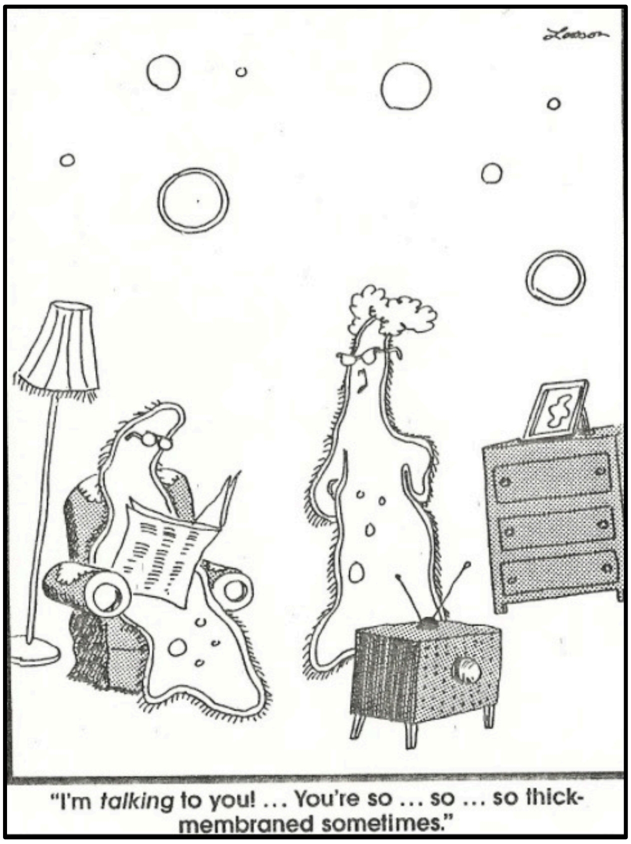
Het ontstaan van leven nieuw leven inblazen

Jan de Leeuw en Lutz Lohse



NIBI conferentie, 11/12 januari 2019

Hand-out, opdrachten, en aanvullende bronnen n.a.v. de workshop

Inhoudsopgave

Opdracht 1: Uitbeelden van protonen gradiënten over een membraan

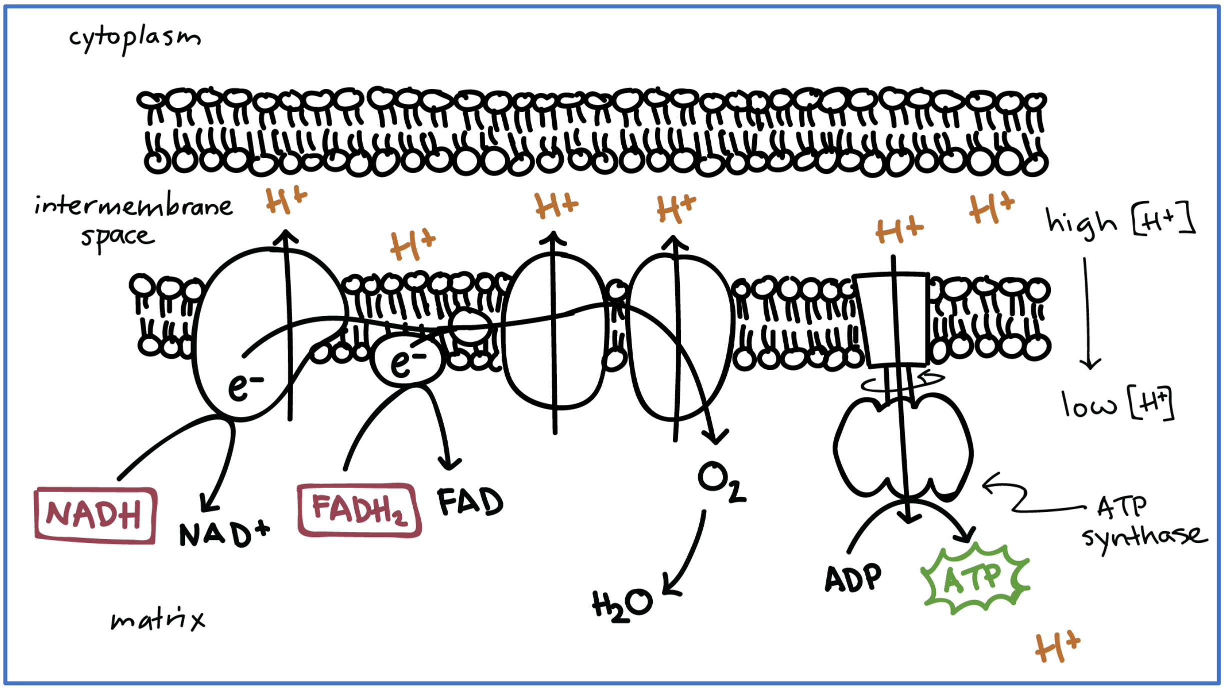
In de twee plastic dozen bevinden zich a) een electronentransportketen (ETS) en b) een ATP synthase (beiden verkregen via origamiorganells.com).
(NB: Deze organellen zijn alvast in elkaar gezet t. b. v. de workshop. Toch is juist het bouwen van organellen onderdeel van het leerproces, leerlingen kunnen dit doen in +/- 30 min)

1. Teken op het A0 vel een binnen en buitenmembraan van een mitochondrium of een bacterieel membraan en rangschik de elektronentransportketen en de ATPase (hieronder niet getoond) volgens onderstaande afbeelding over de getekende membraan.

. 1 bron:origamiorganelles.com

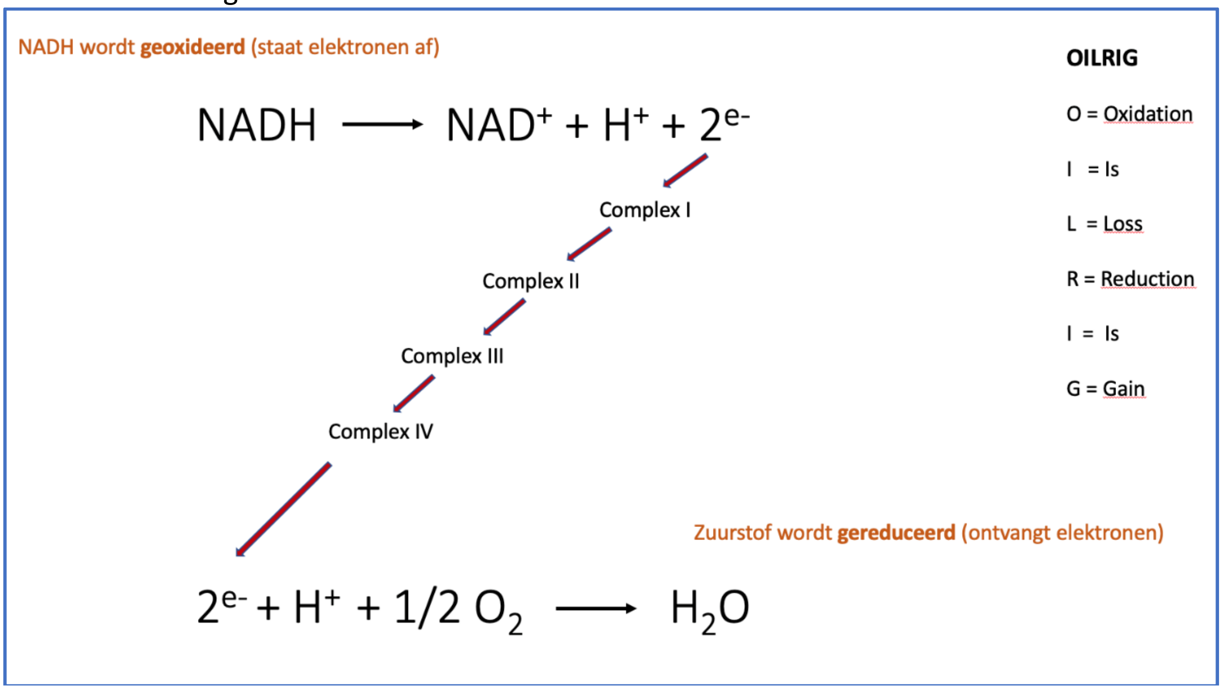
2. De co-enzymen $NADH^+$ en $FADH_2$ staan hun elektronen, verkregen uit de redoxreacties in de glycolyse en het citroenzuurcyclus, af aan de eiwitcomplexen I en II. Hierbij worden $NADH^+$ en $FADH_2$ geoxideerd.
3. De hierbij vrijkomende energie wordt gebruikt om protonen te pompen. Beeld uit hoe de gradiënt over de membraan ontstaat. (zie evt. blz. 5, afb. 1 en 2 voor extra info).
4. Wanneer (en waar) worden de elektronen op zuurstof overgedragen?
5. Zet nu ATP synthase in werking. Hoe wordt ATP geproduceerd? Welke weg leggen de protonen af? Hoe beweegt de rotor in ATP-ase? Leg dat aan elkaar uit!

Afebeeding 1



Bron: Kahn academy

Afbeelding 2



Opdracht 2: Stambomen construeren met ijzerwaren

2.1 Basisopdracht

Construeer van de afgedrukte ijzerwaren in de envelop een fylogenetische stamboom.
(NB: De volledige opdracht is te vinden op
(https://www.scienceinschool.org/sites/default/files/teaserPdf/issue27_phylogenetics.pdf
ook te vinden onder bijlage 5

Pas daarbij onderstaande ‘evolutionaire’ regels toe:

- Organismen die op elkaar lijken zijn waarschijnlijk meer aan elkaar gerelateerd dan organismen die niet op elkaar lijken.
- Veranderingen in morfologie vinden geleidelijk plaats, soms zijn er abrupte overgangen zichtbaar.
- Complexere vormen volgen simpelere vormen op (met uitzonderingen).
- Gespecialiseerde structuren kunnen verloren gaan.

2.2 Evolutie van Eukaryoten

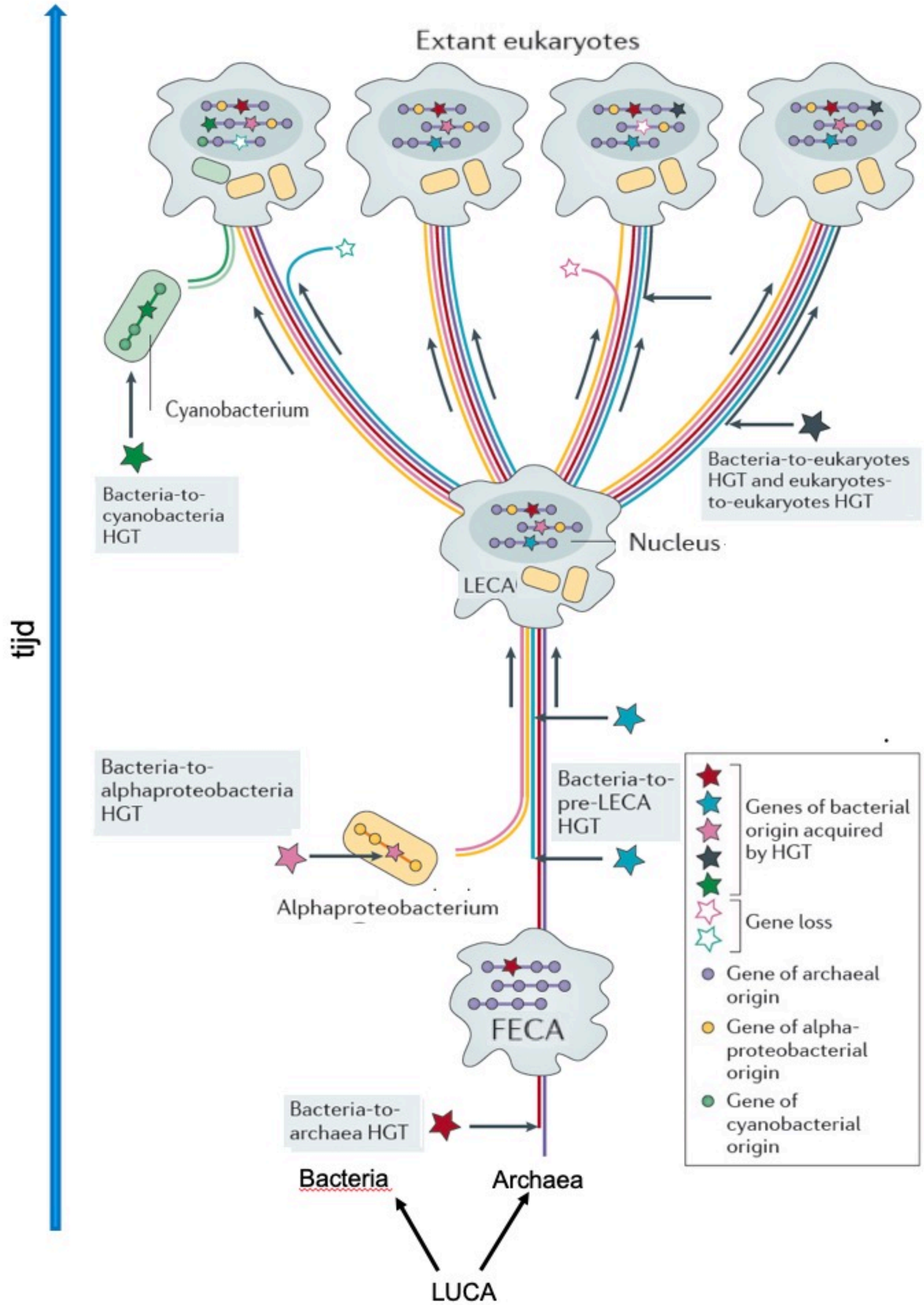
Construeer van de afgedrukte ijzerwaren in de envelop een stamboom met twee domeinen (Archaea en Bacteriën) die aan de basis staan en laat de Eukaryoten hieruit ontstaan. Gebruik de informatie uit de presentatie en bijlage 4.

Opdracht 3: Stambomen construeren met LEGO (open opdracht)

Construeer uit de doos met LEGO onderdelen een fylogenetische stamboom waarin Eukaryoten ontstaan uit de domeinen Bacteria en Archaea. Gebruik hierbij de informatie uit bijlage 1 en 4. Hoe zou je de horizontale overdracht van genen kunnen uitbeelden?

Bijlage 1: Ontstaan van eukaryoten langs de Archaeale lijn

(veranderd naar ‘Archaea and the origins of Eukaryota (zie samenvatting hieronder)



Bijlage 2: Why are cells powered by proton gradients?

Volledige artikel vrij toegankelijk op https://www.nature.com/scitable/topicpage/why-are-cells-powered-by-proton-gradients-14373960

INTERMEDIATE | CELL ORIGINS AND METABOLISM | Lead Editor: Gary Coté, Mario De Tullio

Why Are Cells Powered by Proton Gradients?

By: Nick Lane, Ph.D. (*Research Department of Genetics, Evolution and Environment, University College London*) © 2010 Nature Education

Citation: Lane, N. (2010) Why Are Cells Powered by Proton Gradients? *Nature Education* 3(9):18

The proton gradients that power respiration are as universal as the genetic code itself, giving an insight into the origin of life and the singular origin of complexity.

Aa Aa Aa

Why do virtually all cells "breathe" by pumping protons (hydrogen ions) across a membrane? According to molecular biologist Leslie Orgel, this is the single most counterintuitive idea in biology after Darwin's, and the only one to bear comparison with the concepts of Heisenberg, Schrödinger, and Einstein (Orgel 1999).

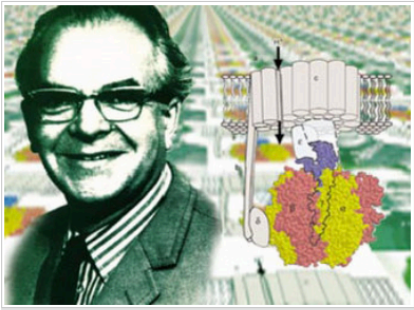


Figure 1: Peter Mitchell and the ATP synthase enzyme
© 1999 Nature Publishing Group Orgel, L. Are you serious, Dr Mitchell? *Nature* 402, 17 (1999). All rights reserved.

Pioneered by the eccentric British biochemist Peter Mitchell (Figure 1), largely in his own research laboratories in a renovated country house in rural Cornwall, the concept was controversial for more than twenty years. This period of controversy was known as the "ox-phos wars" (after "oxidative phosphorylation," the mechanism of ATP synthesis in respiration). The wars drew to an end only after Mitchell received the Nobel Prize in 1978.

There's an irony here. Mitchell's Nobel was for work in chemistry, yet his ideas are actually about the elimination of chemistry. In the same way that the genetic code enables information to transcend chemistry, so Mitchell's proton gradients enable cellular metabolism to transcend chemistry.

The use of proton gradients gives an insight not only into how life got going in the first place, but also, perhaps, its deepest stalling point: the evolution of complex eukaryotic (nucleated) cells, which arose just once in 4 billion years of evolution.

Bijlage 3: Verdergaande bronnen op het web

1. https://www.origins-center.nl

   Nederlands initiatief, gesticht in 2017, waarin onderzoekers uit verschillende disciplines samenwerken aan vragen gerelateerd aan het ontstaan van leven.

2. *Origin of life (biochemistry meets geochemistry)* and
   The symbiotic origin of Eukaryotes

   Professionele (Engelstalige) filmpjes geproduceerd door Bil Martin, Univ. Düsseldorf, te vinden op https://www.molevol.hhu.de/en/movies.html (geschikt voor vwo 5/6)

3. Boek: De belangrijkste vraag van het leven, van Nick Lane (2018, Promotheus)

4. Als je geen zin of tijd hebt om het boek van Nick Lane te lezen
   https://www.youtube.com/watch?v=gLcWfecmZhE

5. Uitbeeld biologie met behulp van origami (gezien op de NIBI)
   https://origamiorganelles.com

6. Artikel op Nature.com (voor onderwijs, vrij toegankelijk)
   Why are cells powered by proton gradients?
   https://www.nature.com/scitable/topicpage/why-are-cells-powered-by-proton-gradients-14373960

7. Woods Hole Oceanographic Institution
   Educatief materiaal uit een van de grootste oceanografische ondezoeksinstituten
   https://divediscover.whoi.edu/hydrothermal-vents/ventbasics/

Bijlage 4: Archaea and the origins of Eukaryotes

Samenvatting Nature artikel (hele artikel is helaas niet vrij toegankelijk)

Review Article | Published: 10 November 2017

Archaea and the origin of eukaryotes

Laura Eme, Anja Spang, Jonathan Lombard, Courtney W. Stairs & Thijs J. G. Ettema

Nature Reviews Microbiology **15**, 711–723 (2017) | Download Citation

A Corrigendum to this article was published on 27 November 2017

This article has been updated

Abstract

Woese and Fox's 1977 paper on the discovery of the Archaea triggered a revolution in the field of evolutionary biology by showing that life was divided into not only prokaryotes and eukaryotes. Rather, they revealed that prokaryotes comprise two distinct types of organisms, the Bacteria and the Archaea. In subsequent years, molecular phylogenetic analyses indicated that eukaryotes and the Archaea represent sister groups in the tree of life. During the genomic era, it became evident that eukaryotic cells possess a mixture of archaeal and bacterial features in addition to eukaryotic-specific features. Although it has been generally accepted for some time that mitochondria descend from endosymbiotic alphaproteobacteria, the precise evolutionary relationship between eukaryotes and archaea has continued to be a subject of debate. In this Review, we outline a brief history of the changing shape of the tree of life and examine how the recent discovery of a myriad of diverse archaeal lineages has changed our understanding of the evolutionary relationships between the three domains of life and the origin of eukaryotes. Furthermore, we revisit central questions regarding the process of eukaryogenesis and discuss what can currently be inferred about the evolutionary transition from the first to the last eukaryotic common ancestor.

Key points

- The Archaea was recognized as a third domain of life 40 years ago. Molecular evidence soon suggested that the Eukarya represented a sister group to the Archaea or that eukaryotes descended from archaea.
- Culture-independent genomics has revealed the vast diversity existing among the Archaea, including the recently described Asgard superphylum. Phylogenomic analyses have placed the Asgard archaea as the closest prokaryotic relatives of eukaryotes.
- Comparative genomic analyses have reconstructed a complex last eukaryotic common ancestor. However, how and in which order these complex eukaryotic features evolved in an Asgard archaea-related ancestor remains largely unclear.
- Genomic investigation of Asgard archaea showed that they carry several genes formerly believed to be eukaryotic specific, illuminating early events during eukaryogenesis.
- Fully understanding the process of eukaryogenesis requires finding answers to several challenging and intertwined questions. Although we have seemingly answered some of these questions, others remain fiercely debated, and new questions continue to arise.

Bijlage 5 Phylogenetics of man-made objects: simulation of evolution in the classroom

(uit scienceinschool.org 2011, Vol 27, 26-13)

Image courtesy of Michael Apel / Wikimedia Commons

Juvenile male damselfly (*Calopteryx virgo*)

Phylogenetics of man-made objects: simulating evolution in the classroom

Image courtesy of kevincole / Wikimedia Commons

American avocet (*Recurvirostra americana*)

Evolutionary relationships can be tricky to explain. By using simple, everyday objects, your students can work them out for themselves.

By John Barker and Judith Philip

Birds, bats and insects all have wings; horses, millipedes and crocodiles all have legs. Many unrelated species can be grouped by physical similarities – that is one of the problems with studying morphological phenotype to determine evolutionary relationships. Convergent evolution can result in apparently similar structures. Although the end product may be the same (e.g. the presence of wings), the starting points can be very different. Some organisms that may appear similar and hence related are actually widely separated from each other in the evolutionary tree.

At a molecular level, DNA and protein studies can be used to produce a family tree by looking at the differences between homologous sequences: sequences that are thought to have evolved from a common ancestor. Kozlowski (2010) describes an excellent activity to demonstrate this in a classroom, but there is a sense of being removed from the study – the data required is simply downloaded and used. This article provides a complementary, more hand-on introduction to evolutionary studies, in which the students gather all the necessary data themselves before considering the underlying principles.

In this classroom activity, your students can use a wide range of objects to create an artificial phylogeny based on morphology. The family tree that they produce will be artificial in the sense that the objects used have not actually evolved from each other. However, the problems faced and the questions posed are similar to those addressed by palaeontologists using specimens of fossils, or by entomologists using specimens of dead insects in museum cabinets.

The activity, which takes approximately 30 minutes, is suitable for a wide range of students, from the age of about 15 up to postgraduate level.

It allows students to:

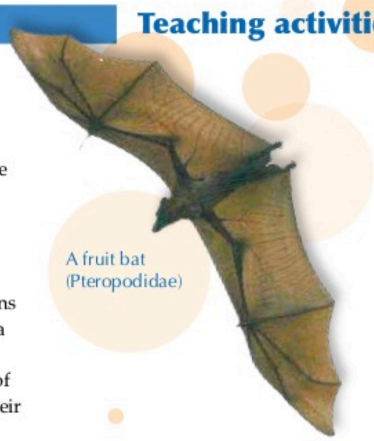
1. Use morphology to make an 'evolutionary' tree.
2. Link morphology to adaptations and consider the definition of a species.
3. Hypothesise the morphology of missing links and state how their hypothesis could be tested.
4. Consider the challenges and limitations of using evolutionary trees based on morphology and on DNA sequences.
5. Investigate for themselves the concepts of divergent, convergent and parallel evolution.
6. Present, discuss, defend and evaluate a proposed evolutionary tree.
7. Recognise the expertise required by scientists when making evolutionary trees.

REVIEW

- Biology
- Evolution
- Ages 14-19

Evolution is a tricky concept to understand. This article describes an unusual but simple classroom activity, using cheap and easily available materials to teach some of the most basic principles of evolution. More specifically, through the use of evolutionary trees, students can investigate the phenomena of divergence, convergence and parallel evolution. It's also fun!

Michalis Hadjimarcou, Cyprus



A fruit bat (Pteropodidae)

Image courtesy of Peter van der Sluijs / Wikimedia Commons

Guiding principles

There are four guiding principles used to produce an evolutionary tree based on morphology:

1. Organisms that resemble each other in many ways are probably more closely related than are organisms that resemble each other only slightly. That is, the greater the similarity in structure (the more features in common), the closer the probable relationship between two forms.
2. Evolution is usually the result of a gradual accumulation of small changes in structure (and function) but occasionally there are larger changes.
3. In general, simpler forms give rise to more complex ones and smaller forms to larger ones, although there can be exceptions.
4. Evolutionary processes do not go into reverse, but specialised structures can be lost.

Activity: evolution in the classroom

One version of this activity uses metal objects such as nails, screws, staples, paperclips and drawing pins. The greater the number of objects used, the longer the activity will take.

As a guide, it will take the students around 15 minutes to sort out the evolutionary relationships and 10-15 minutes for feedback and discussion. The time required could be shortened by using fewer objects or using

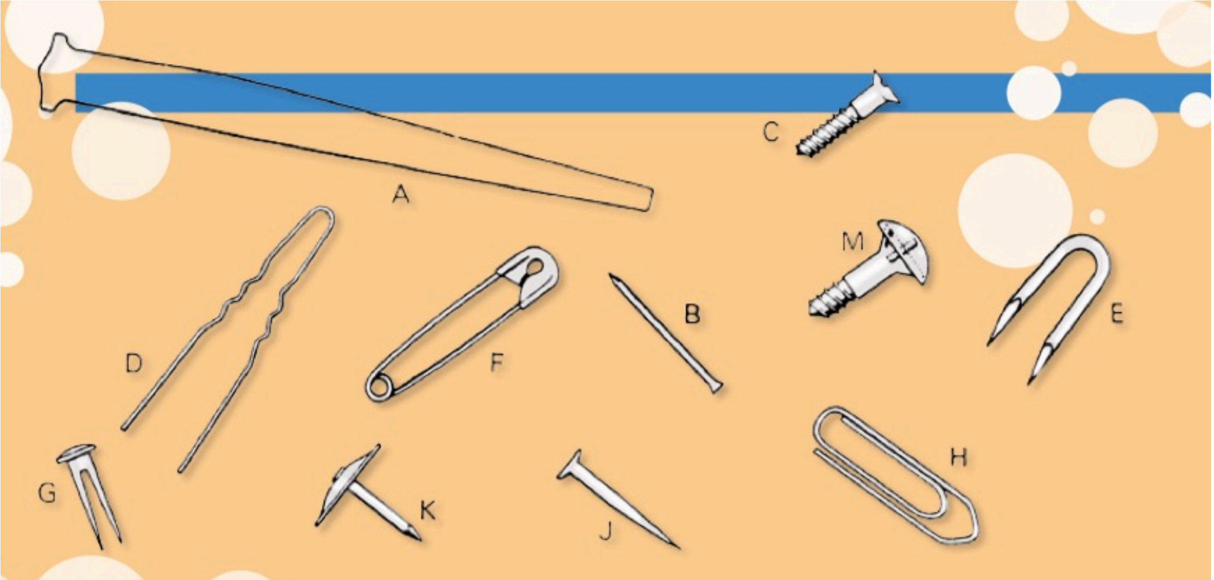


Image courtesy of John Barker

printouts instead of real objects – although it is more fun to handle real objects.

Materials

For each group, you will need one example each of some or all of the following metal objects (figure 1). Alternatively, you can use printouts of the objects (see the procedure, below).

- 75 mm tack [A]
- 20 mm nail [B]
- 20 mm screw [C]
- Hairpin (50 mm) [D]
- Staple (25 mm) [E]
- Safety pin (40 mm) [F]
- Split rivet (20 mm) [G]
- Paperclip (32 mm) [H]
- 25 mm tack [J]
- Upholstery pin (20 mm) [K]
- 13 mm nail [L]
- Mirror screw (20 mm) [M]
- Insulated staple (13 mm) [N]
- Round-headed paper fastener (20 mm) [O]
- Flat-headed paper fastener (20 mm) [P]
- Round-headed screw (25 mm) [Q]
- 50 mm nail [R]
- Drawing pin (6 mm) [S]
- Hook (20 mm) [T]
- Kirby grip [W]
- Bolt (65 mm) [Z]

Note, however, that it is not essential that the objects are exactly the size stated.

Procedure

1. Divide the class into groups.
2. Either:

   a) Hand out one of each of the objects shown in the figure to every group. Make sure each object has a letter.

   b) Download the pictures of the objects in figure 1 from the *Science in School* website[w1] and cut them out, keeping the letter with the picture. Use the printouts as though they were the actual objects.
3. Ask your students to arrange the objects to form a possible evolutionary series, using the four guiding principles. Encourage them to choose the smallest, simplest form as the probable common ancestor for the group and then try to arrange the others as branches of a tree derived from this ancestor.
4. Ask your students to record their trees using the letters associated with the objects.
5. Explain the concepts of divergent, convergent and parallel evolution. Then get your students to mark their trees to show possible divergence, convergence or parallel evolutionary developments.

Some solutions and discussion points

Some lines of evolution seem very obvious whereas other specimens will be quite difficult to place. Some may fit in several positions.

- The common ancestor is probably L — a small, simple form with a tiny head and simple shaft.
- L → B → R is an obvious line showing increase in size.
- L → J → A is a parallel line with a square shaft and larger head between Land J. L or B or J could have → C by an increase in complexity of head and shaft. (L or B seems the more likely ancestor because J has a square shaft.)
- C → Q → Z is a line showing an increase in size, increase in complexity of head, and finally a change in the shaft. Probably C → T through a change in head accompanied by slimming of the body.
- L → S → K is a line showing an increase in size and specialisation of the head. Probably S → P through an increase in size, but the material is different so it is possible that B or J → P, in which case there would be a convergence between P and S / K.
- Is G part of this evolutionary series? Either S or P could → G by a thickening and subsequent splitting

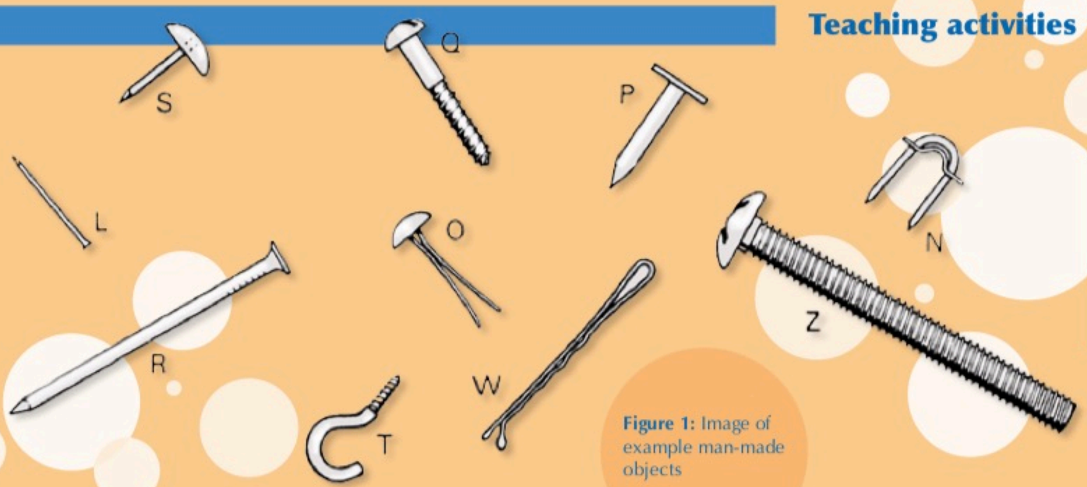


Figure 1: Image of example man-made objects

of the shaft. Probably G → O by a combination of elongation and slimming (a sort of eel-like series).

- M presents an interesting problem: of its two parts, one, the base component, is clearly very close to C in structure; the other part, the top component, shows similarities to Z but the head is smooth, not grooved. M also shows similarities to S but the shaft is threaded, not smooth. This is probably part of the radiation from C but it is clearly convergent to S. Do the two components represent two sexes (illustrating sexual dimorphism) or is M really a curious hybrid between descendants of C and S?

All the evolutionary series considered so far basically have a straight shaft and a single axis (exceptions are G and O where the shaft is double; T, which has a curved head, is another highly divergent type). We could say that all these forms are members of a single order – Orthos (from the Greek for 'straight') or some similar name. The rest of the objects are bent in various ways – Sinuos (from the Latin for 'curve') or some similar name. Of the curved objects, the simplest form is probably E so this is likely to be nearest to the common ancestor.

- Probably L → E by loss of its tiny head and bending of the shaft but it is just conceivable that T → E by loss of the screw thread and further bending of the head. It seems more likely that T is convergent to the series descended from E.
- E → N by addition of the plastic insulation.
- E → D by elongation and slimming of the two sides and appearance of waves.
- D → W by further asymmetrical specialisation of the two sides.
- H and F look as though they are related, with H → F by addition of material to form a head. H might be derived from E by slimming and bending, possibly with common ancestry with D; extra bends formed later, thus E → X (not represented in the collection – an as yet undiscovered fossil) → D → W and X → H → F.
- G and O have double shafts – could they be part of the Sinuos order? O could be derived from E by slimming and development of the centre into a sort of head, and then O could develop into G by strengthening and solidification. In this case, there would be strong convergence between G and S / P.

Within each 'order', there are several divergent lines. Series showing increases in size are common in the Orthos group; they also show variety in the development of the head and of the shaft, both independently and together. The Sinuos group shows variety in the bending of the two shafts; they generally lack heads – which may make it more probable that G and O are Orthos and not Sinuos.

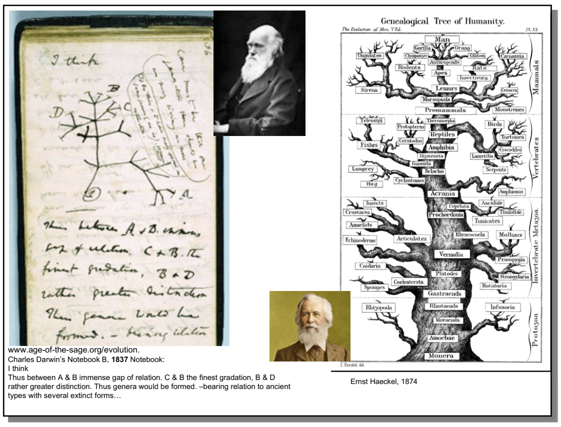
Your students may have thought out quite a different series of evolutionary lines but as long as they can justify them using the four general principles, then each series is just as credible. If the objects were extant organisms, then there would be other possible lines of argument – such as studies of their molecular characteristics or of their embryology – which might support some hypotheses while discounting others and so indicate more precisely the probable evolutionary series.

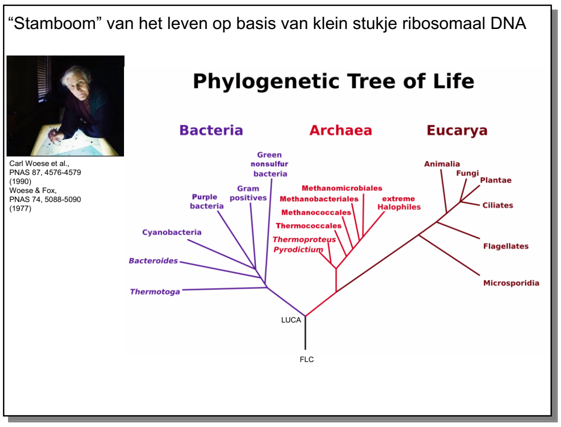
Variations

This type of activity can also be carried out with a range of other objects, for example biscuits or dried pasta. These materials can introduce another variable – that of colour. Do the colour differences represent camouflage, for example, or sexual dimorphism?

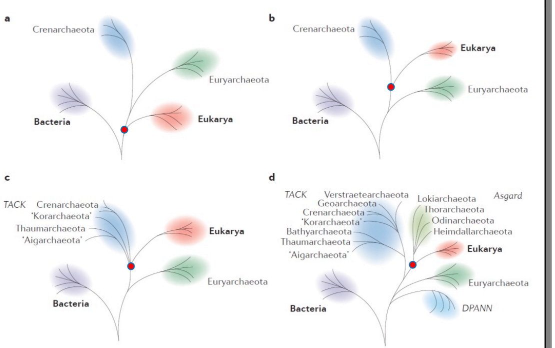
For a simple, 20-minute activity, a small group of objects can be used to represent the problems sometimes faced by palaeontologists. New specimens can be introduced as if they were recently discovered fossils. How can these new finds be accommodated in the tree?

Bijlage 6 Dia's uit presentatie

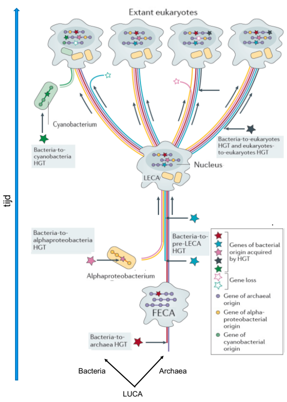




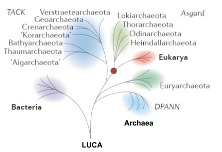
Sterk toenemende diversiteit van Archaea over de laatste 40 jaar (a via b en c naar d) en de relatie tot eukaryoten



Eme et al., Nature Rev. Microb. 15, 711-723 (2017)

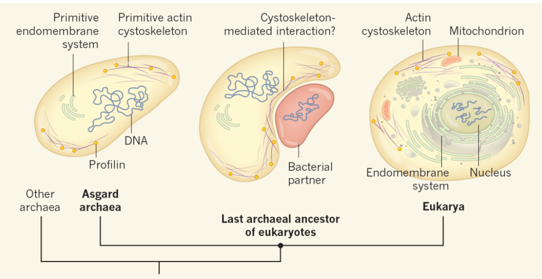


Ontstaan van eukaryoten langs de "Archaeale lijn" via horizontaal genen transport (HGT) voor en na unieke endosymbioses

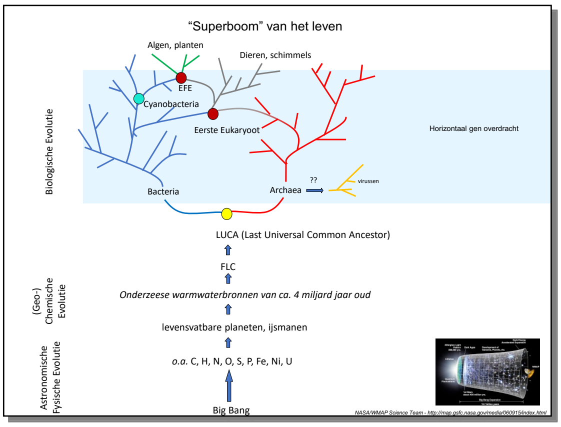


Modified after Eme et al., Nature Rev. Microb. 15, 711-723 (2017)

Vroege evolutie van Eukaryoten
door een eenmalige endosymbiose van een **Archeon** en een **Bacterie**



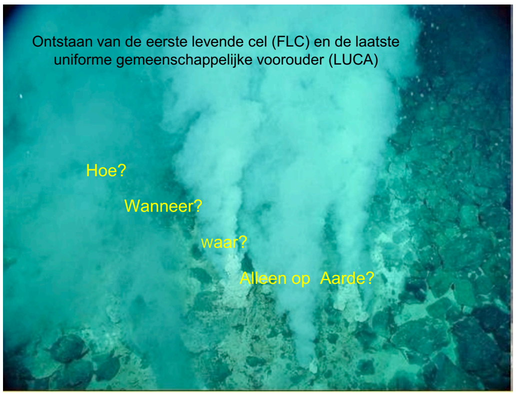
Laura Eme & Thijs J.G. Ettema; Nature, 562, p.352-353 (2018)



Metabolisme micro-organismen

Energiebron	Licht	foto-			-troof
	Licht & redoxreactie	mixo-			
	Redoxreactie	chemo-			
Elektronendonor	Organische verbinding		organo-		
	Anorganische verbinding		litho-		
Koolstofbron	Organische verbinding			hetero-	
	Anorganische verbinding			auto-	

Wikipedia



Voorwaarden voor het ontstaan van leven op Aarde
of andere "levensvatbare" planeten

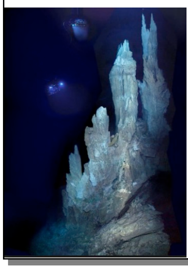
1) ***Energie en Koolstof (C).*** Continue toevoer van reactieve Koolstof en Energie om de noodzakelijke moleculen te kunnen maken, om de levende cel goed te laten functioneren en om te delen.
2) ***Katalysatoren*** om noodzakelijke chemische omzettingen in een levende cel snel en foutloos te laten verlopen bij "normale" temperatuur en druk.
3) Het ***verwijderen*** van ***afvalproducten***, o.a. om de reacties in de juiste richting te laten verlopen.
4) ***Compartimentvorming*** om binnenkant van de cel te scheiden van de buitenkant.
5) Aanwezigheid van ***erfelijk material***, RNA, DNA om te coderen voor de vorm en functie van de levende cel.

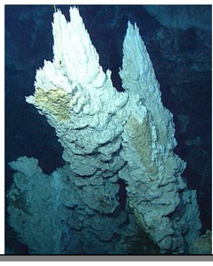
Vrij naar Nick Lane in: De belangrijkste vraag van het leven, Waarom is het leven zoals het is? Prometheus, 2018

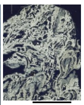
Deborah Kelley
University of Washington

Onderzeese warmwaterbronnen,
"white smokers",
maar dan in de oertijd

Ontdekking onderzeese warmwaterbronnen Lost City, 2000



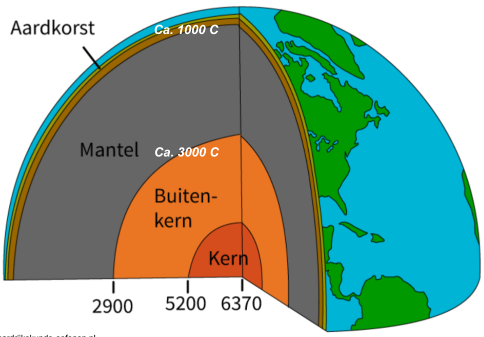




500 µM

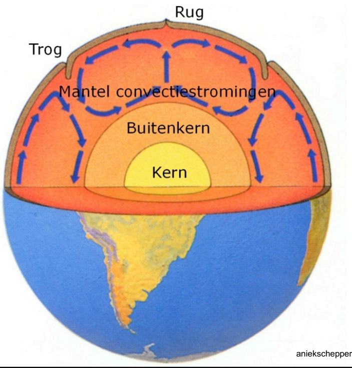
Russell MJ, Hall AJ. The emergence of life from iron monosulphide bubbles at a submarine hydrothermal redox and pH front. *J. Geol. Soc. Lond*. 154:377-402 (1997)

Een kijkje in de aardbol



www.aardrijkskunde-oefenen.nl

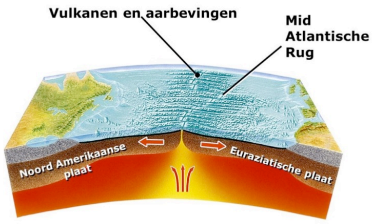
Convectiestromen in de mantel veroorzaken het "drijven" van de continenten waardoor de Aarde, geologisch gezien, er steeds anders uitziet

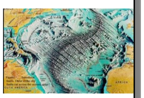


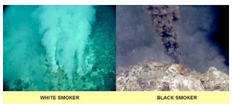
aniekscheppers.wordpress.com

Nieuwvorming Aardkorst door stollend magma vanuit mantelgesteente

Divergent plaatbeweging
Oceanische plaat beweegt uit elkaar

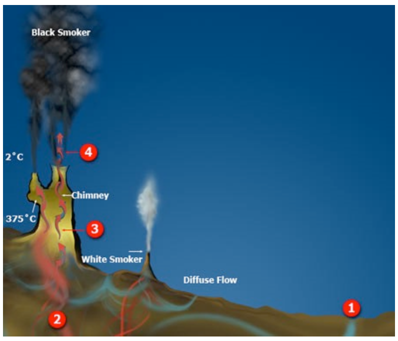






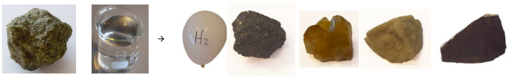
meneerschreurs.weebly.com

Black vs White smokers



Serpentinisatie in “white smokers”

De reactie van (zeer heet) water met het mineraal olivijn in nieuwgevormde aardkorst op grote diepte onder onderzeese oer-warmwaterbronnen:

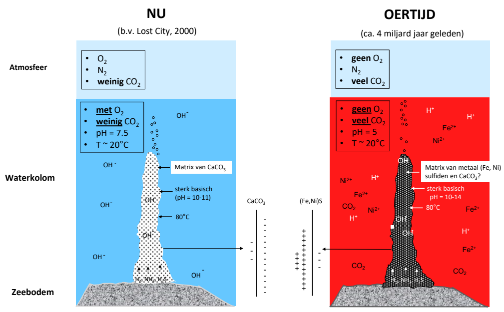


Olivijn + Water → ***Waterstof*** + Magnetiet + Kwarts + ***Bruciet*** + Serpentiniet

Voor de (geo)chemici onder ons:

$3\ Fe_2Si0_4 + 2\ Mg_2SiO_4 + 5H_2O \rightarrow 2\ \mathbf{H_2} + 2\ Fe_3O_4 + 3\ SiO_2 + \mathbf{Mg(OH)_2} + Mg_3Si_2O_5(OH)_4$

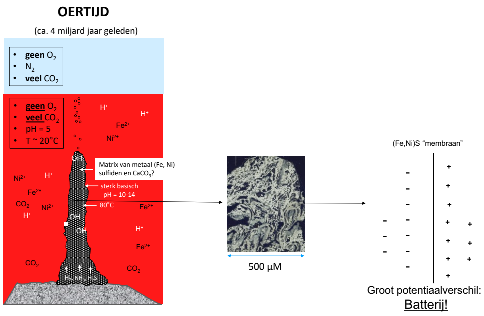
Onderzeese warmwaterbronnen (white smokers)



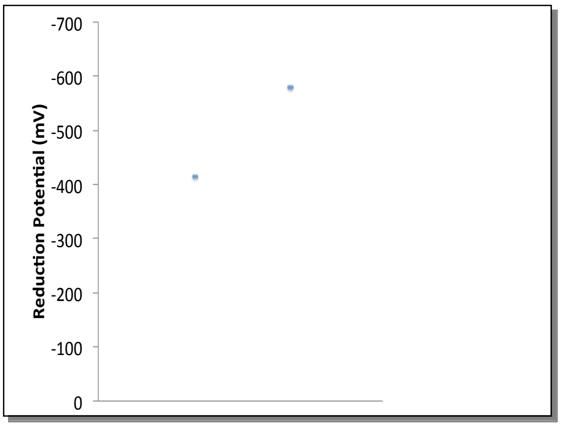
$CO_2 + H_2 \not\rightarrow HCOOH$

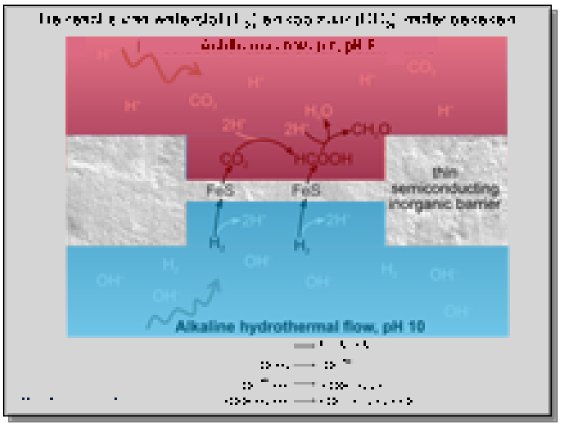
$CO_2 + H_2 \xrightarrow{(Fe,Ni)S} HCOOH$

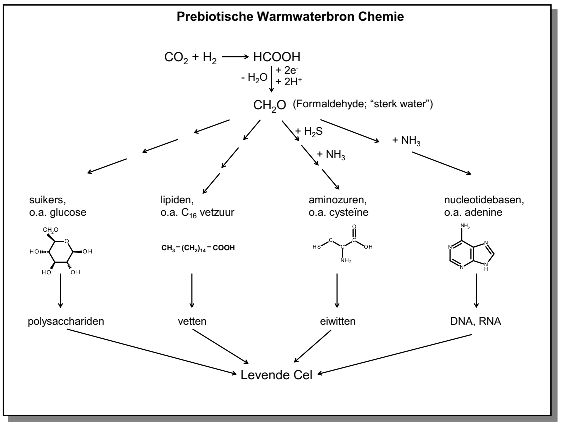
Warmwaterbronnen van toen als constante bron van “duurzame” energie in de vorm van een giga-batterij.



$CO_2 + H_2 \xrightarrow{(Fe,Ni)S} HCOOH$

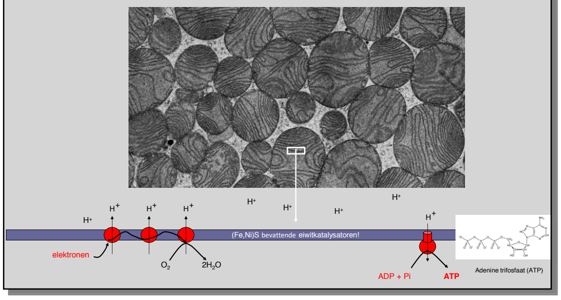

Reduction Potential (mV)
-700
-600
-500
-400
-300
-200
-100
0


CO2
H2O
2H+
CH2O
HCOOH
FeS
FeS
thin semiconducting inorganic barrier
2H+
2H+
H2
H2
Alkaline hydrothermal flow, pH 10

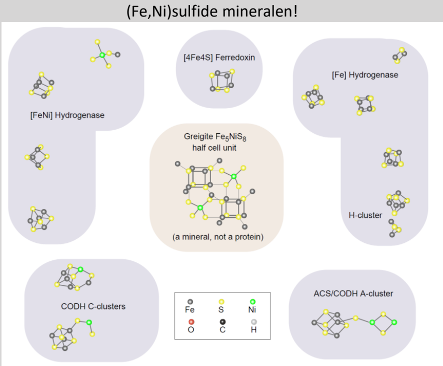

Prebiotische Warmwaterbron Chemie
CO2 + H2 → HCOOH
- H2O
+ 2e-
+ 2H+
CH2O (Formaldehyde; "sterk water")
+ H2S
+ NH3
+ NH3
suikers,
o.a. glucose
lipiden,
o.a. C16 vetzuur
aminozuren,
o.a. cysteïne
nucleotidebasen,
o.a. adenine
polysacchariden
vetten
eiwitten
DNA, RNA
Levende Cel

Peter Mitchell
(1920-1992)

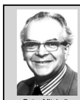
Proton (H^+) gradiënten over membranen, "batterijen", zijn **universeel** en komen in ***alle*** organismen voor



"Hot spots" (co-factoren) in energie-gerelateerde enzymen zijn: (Fe,Ni)sulfide mineralen!



Russell MJ, Martin W. The rocky roots of the acetyl CoA pathway. *Trends in Biochemical Sciences* 29: 358063 (2004).



Peter Mitchell
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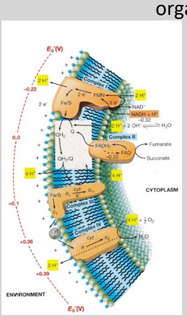
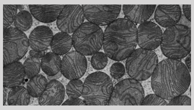


Prokaryotische membraan
Bron: Brock, Biology of Microorganisms, Pearson

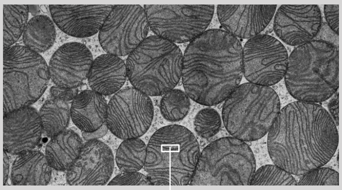


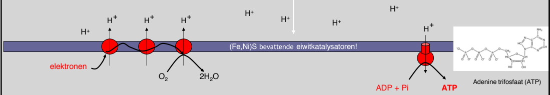
Eukaryotische membranen (mitochondria)

(Fe,Ni)S Enzymcomplexen I - IV

Proton (H^+) gradiënten over membranen, "batterijen", zijn **universeel** en komen in ***alle*** organismen voor

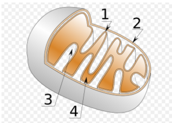
Peter Mitchell
(1920-1992)

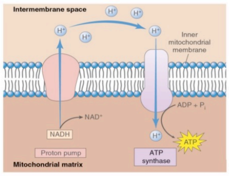




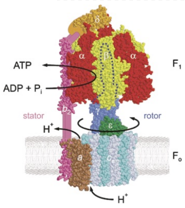
Chemiosmose

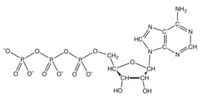
Peter Mitchell
(1920-1992)





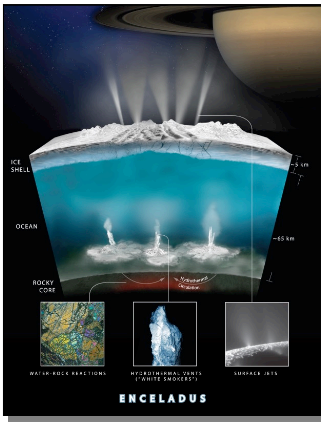
Univ. Utrecht





Adenine trifosfaat (ATP)

Yi Qin Gao et al., Cell (123), 195-205 (2005)



Buitenaards Leven?!?

Microbieel leven op de ijsmaan Enceladus van Saturnus in onderzeese warmwater bronnen aangedreven door getijdekrachten van Saturnus?!?

NASA/JPL-Caltech/Southwest Research Institute